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AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

SURVEILLANCE RESEARCH LABORATORY

SALISBURY, SOUTH AUSTRALIA

TECHNICAL MEMORANDUM

SRL-0073-TM

SOFTWARE FOR PREDICTION AND ANALYSIS OF GROUND WAVE PROPAGATION LOSS

M.J. WHITINGTON and R.M. THOMAS

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SUMMARY

This document describes a variety of in-house and externally written software which has been used in High Frequency Radar Division for the prediction and analysis of ground wave propagation losses. Applications of the software have included the determination of sizes of HF array buffer zones and intersite separations between transmitter and receiver for Over-The-Horizon Radars of the Jindalee Operational Radar Network. The same software may also be useful for communications and broadcasting applications, and can be made available upon consultation with the authors.

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1 INTRODUCTION

This Technical Memorandum describes software which has been used within High Frequency Radar Division (HFRD) for the prediction of ground wave propagation behaviour and the analysis of ground wave loss measurements. The work has been carried out mainly in support of the site selection programme for the Jindalee Operational Radar Network (JORN), for which it was necessary to determine array buffer zones and Rx-Tx intersite separations for a range of local terrain and soil properties. One outcome of the work has been the development of the frequency-dependent ground wave loss technique for measuring effective ground conductivity and relative permittivity (or dielectric constant)(ref 1, 2).

The available programs which run on the HFRD VAX network include the code GRWAVE for the calculation of ground wave field strength and basic transmission loss using CCIR definitions (ref 3, 4), a non-linear least squares program for the optimisation of soil conductivity and dielectric constant which uses GRWAVE in subroutine form, programs to compute and plot ground wave skin depth in soil of given properties, a version of Ott's program WAGNER for the computation of ground wave loss over inhomogeneous, irregular terrain (ref 5) and WAGSLAB, Hill's adaptation of WAGNER which accounts for the existence of a dielectric layer such as snow, ice or vegetation on the soil surface (ref 6). The program EMPIRICAL implements the relatively simple and convenient equations of Knight and Robson for the calculation of approximate ground wave losses (ref 7). In addition we have the program GWLSF which is a non-linear least squares adaptation of Forbes' GWAVE (ref 8), and a program to plot contours in soil parameter space of the root mean square deviation between measured and computed frequency-dependent basic transmission loss.

In this Memorandum we provide an overview of the available software programs, their functions and representative results. We avoid matters of fine detail, anticipating that the reader will become concerned with the latter only when he or she reaches the point of using the software. We then recommend consultation with the authors, and use of the extensive HELP files which have been prepared.

2 HFRD COMPUTING ENVIRONMENT

The following sections contain an overview of the HFRD Computing Environment (at the time of writing, and anticipating the combination of our two VAX clusters into one super cluster).

2.1 HARDWARE

The HFRD VAX computing resource is a Classified network consisting of a VAX cluster and a number of other machines connected via DECnet over thinwire ethernet. The network is connected to DSTO Salisbury's Classified network. The cluster comprises two 8250 VAX processors (DARSC, DADTC), a 6220 (DAMSC),a 9000-420 (DAJAV), two 3600 series VAXservers (disk servers) and around forty VAXstation 2000 and 3100 workstations. The workstations are VAX systems in their own right, being boot and disk served by the two VAXserver 3600 systems. All processors run the VMS 5.4 operating system.

Nodes DADTC and DARSC, the VAX 8250 processors, have a single, 1 VUP, scalar CPU with 16Mb memory.

Node DAMSC, the VAX 6220 processor, has two 3 VUP Symmetrical MultiProcessing, scalar CPUs for a total of approximately 6 VUPs and 64Mb memory.

Node DAJAV, the VAX 9000-420 processor, has two 40 VUP Symmetrical MultiProcessing, scalar CPUs for a total of approximately 80 VUPs, with 256Mb memory. Each scalar CPU (on DAJAV) has an integrated, tightly coupled VECTOR CPU, providing 125Mflops peak, for a total of 250Mflops peak. Average performance for real problems is usually about 25% of peak performance, or approximately 30Mflops per vector CPU. Depending on workload characteristics and degree of vectorization this can be lower.

By comparison, for inline floating-point operations on a 40 VUP scalar CPU, a performance of 10 Mflops could be expected.

2.2 SOFTWARE

Recommended disk space for Ground Wave programs plus data is 5 to 10Mbytes. All Ground Wave programs on the HFRD network reside in sub-directories below RES$IEGROUP:[GROUND_WAVE] [.GWAVE] [.SKINDEPTH] [.FORTRAN] [.LIBRARY]. The object code for each module in a directory resides in a .OLB file in the top level directory, and a .HLB help library (text) also exists in the top level directory. The programs are written in FORTRAN 77 plus VAX extensions (very similar to Microsoft FORTRAN 77).

Plotted output is generated using an inhouse plotting package called PLOTLIB, but basic plotting calls are simple and obvious to convert to other systems, with the only exceptions being the axis labelling routine and the contour plotting routine (sources for both can be provided).

Real numbers are normally defined as REAL*8 to preserve accuracy. Where REAL*4 or REAL representation is used the module may be in an original (external to HFRD) form, the type REAL on some other computers being a close approximation to REAL*8. Some other HFRD routines use REAL*4 when no potential for significant errors exists.

3 PROGRAMS

We now describe the programs, all written in FORTRAN, which we have found to be particularly useful tools for ground wave analysis and modelling. Wherever feasible, the description of each program concludes with an example of the program output.

3.1 GRWAVE

This CCIR-recommended code due to Rotheram (ref 3, 4) computes ground wave field strength and basic transmission loss (ref 9, 10) over smooth, spherical, homogeneous Earth paths of any length and for frequencies between 10 KHz and 30 MHz.

It also allows for refractive effects due to an arbitrary exponential atmosphere, but in the absence of independent atmospheric measurements it is customary to assume an atmospheric scale height of 7.35 km and a surface refractivity of 315 N-units which is very nearly equivalent to the effective Earth radius factor of 4/3 commonly used in other radio propagation problems.

The program requires interactively entered input values for the radio wave polarization (whether horizontal or vertical), the heights of the end points of the path above the spherical Earth, the radio frequency, the effective homogeneous conductivity and relative permittivity of the soil along the path, the minimum and maximum distances from the transmitter and the step size in distance along the path for which calculations are required. The calculations are carried out with three different methods depending on distance from the transmitter and on the heights of the terminals. At the farthest distance, in the radio wave diffraction zone, the residue series is used, converging for surface terminals at distances beyond about $10\lambda^{1/3}$ km, with the radio wavelength λ in metres. At short distances for surface terminals, extended Sommerfeld flat Earth theory is used which converges out to a distance of about $15\lambda^{1/3}$, overlapping with the residue series and usually agreeing with it to better than 0.1 dB. Geometric optics is used for elevated terminals within the radio horizon.

Appendix I gives the HELP file for GRWAVE. Appendix II gives a typical output for GRWAVE, in this case for a sea-water path with a conductivity of 5 Siemens/m, dielectric constant of 80, for the standard exponential atmosphere, vertical polarization, surface terminals, a frequency of 10 MHz and distances of from 2 to 50 km at 2 km intervals. The changeover from extended Sommerfeld flat Earth theory to the residue series method takes place at 18.87 km. Sample curves for other propagation conditions, which are useful for checking one's own GRWAVE output, are to be found in references 3 and 4.

3.2 GRWAVE$FIT

This FORTRAN program is used to perform a non-linear least squares fit of basic transmission loss computed by GRWAVE (in subroutine form) to experimental values of basic transmission loss measured in dB at frequencies across the HF band (ref 2). Effective earth conductivity and relative permittivity are optimised in the least squares process which is based on the algorithm of Marquardt (ref 11) and which combines the best features of the Gauss (Taylor Series) method close to the solution, with the method of steepest descent far from the solution, in order to provide rapid convergence. It is particularly useful for problems in which the parameters to be optimised do not enter linearly into the model, as indeed is the case for conductivity and permittivity in GRWAVE.

A general discussion of non-linear least squares estimation may be found in references 12 and 13. Reference 14 describes the least squares package itself. The quantity which is minimised in the procedure is the sum of squares of the weighted residuals given by

$$S(p_j) = \sum_{i=1}^{N} [C_i(f_i,P_j) - M_i]^2 \,/\, V_i \ , \ j=1 \ , \ J \qquad (1)$$

where the loss C_i (i=1,.....,N) is computed by GRWAVE (see section 3.1 above) for frequency f_i and adjustable ground parameters $p_1,.....,p_J$, where $M_1,.....,M_N$ are the experimental measurements which are read from a data file and assumed to be log-normally distributed and $V_1,.....,V_N$ are their estimated variances which depend on the particular measurement technique.

The program involves an HFRD-written main program which runs interactively. The user is prompted for the name of the ground wave data file, the name of the output file, the fit parameters which are required to be optimised and their initial values.

After the main program reads the file of experimental ground wave data, the least squares code is entered which first calls GRWAVE in subroutine form to compute the losses at the measured frequencies for the assumed initial values of the parameters. The sum of squares (equation 1) is then formed and minimised, producing improved estimates for the adjustable parameters. Iterations are carried out on this sequence of steps until successive parameter estimates differ by less than 10^{-5} in relative terms. At this point the solution is deemed to have been found.

Appendix III gives an example of program output, listing the input values, results at each iteration and final results for the solution parameters, together with approximate 95% confidence limits, fit residuals and assorted statistical information which may be interpreted with the help of ref 14. The data were measured over a fresh water path on Lake Alexandrina and the accuracy of the derived least squares solution has been confirmed by independent measurements (ref 2). Figure 1 gives an idea of the quality of the fit obtained for this particular set of data.

It is of particular interest to note that, providing the measured decibel data are normally distributed, then the minimum value of S (see equation 1) should follow a chi-square distribution with (N-J) degrees of freedom. Consequently there exists a "rule of thumb" that for a model to provide an acceptable fit to measured data, the "reduced" variance of residuals given by the ratio $S_{min}/(N-J)$ should have a value of order unity (ref 13).

As with GRWAVE, a HELP file exists to assist the user of GRWAVE$FIT.

3.3 EMPIRICAL

Subroutine EMPIRICAL implements the empirical formula of Knight and Robson (ref 7) for ground wave field strength calculation. We have included basic transmission loss as defined by CCIR (ref 9, 10) as an additional output quantity.

The advantage of this routine over GRWAVE is that it is simple and very quick to run. The disadvantage is that results can be inaccurate by up to 2.5 dB. The results are nevertheless useful for providing approximate answers in the field and for indicating initial values of parameters to be optimized in GRWAVE$FIT.

As with the other programs, a HELP file exists to assist the user. Use of the routine is restricted to distances in km less than about $12\lambda^{1/3}$, where λ is the wavelength in metres.

3.4 SPACE$PLOT

This program maps the variation of the sum of squares $S(p_j)$ given by equation (1) in parameter space $(p_1, p_2, \ldots, p_J)$ for a given set of observational loss data M_i. Most commonly we use J=2, for conductivity and relative permittivity. The program accepts numerous inputs interactively, starting with the name of the file containing observational ground wave loss data, followed by the model to be used to compute theoretical losses (either GRWAVE or EMPIRICAL may be selected), the parameters required by either GRWAVE or EMPIRICAL, and finally the number (up to 100) of conductivity and permittivity values as well as their minimum and maximum values to be passed to the contour plotting routine. The output appears as an A4 portrait format plot of contours in $\sqrt{S(p_j)}$. The plot can also be queued to the HP plotter if desired.

Output plots are shown in figures 2 and 3 for the data file involved in Appendix III. Figure 2 shows the exact contours given by GRWAVE, together with the solution of GRWAVE$FIT. Figure 3 is similar but the contours are given by EMPIRICAL. Comparison of the two figures shows that the minimum for the EMPIRICAL contours is well removed from the GRWAVE$FIT solution, demonstrating the approximate nature of the EMPIRICAL calculation.

A HELP file is available to assist the user of this program.

3.5 WAGNER and supporting programs

This program due to Ott (ref 5) implements a step-wise integral equation solution to the problem of ground wave transmission loss over inhomogeneous and irregular terrain. It has been employed within HFRD to model the effects of isolated hills along a transmission path (ref 15), and also to model the effects of arbitrary terrain profiles. Terrain profiles are entered into a data file (TERRAIN.DAT) by running the in-house interactive program TERRAIN$GEN which permits the user to select a terrain type from (1) smooth spherical Earth, (2) sinusoidal undulations, (3) gaussian hills, or (4) arbitrary terrain. TERRAIN$PLOT is a program which may be run to plot a graph of altitude versus distance. HELP files are available for both TERRAIN$PLOT and TERRAIN$GEN to facilitate their use.

When implemented on host machines of limited word length the program WAGNER is susceptible to numerical instability for higher frequencies, longer paths and more rugged terrains, and must be used with care. Accuracy may be improved by reducing the step size along the path, but at the expense of increasing computation time which varies inversely as the square of the step size. In order to run more reliably on our VAX system (4 byte single precision), our version of WAGNER, named W7D is double precision coded and its characteristics with regard to convergence and accuracy have been studied and reported in ref 16. These findings have been incorporated into program TERRAIN$CHECK which accepts a file of terrain and radio frequency data as input and calculates for the user of W7D the maximum step size in path length which can be reached before instability sets in. It is recommended to use this maximum step size in order to avoid unnecessarily long computation times which can amount to many hours for step sizes as small as 10 metres. The results of TERRAIN$CHECK are displayed on the screen and written to a file and should be taken into account by the user before running W7D. A HELP file is available for TERRAIN$CHECK.

The program W7D prompts the user for a number of inputs: (1) output file name for the results, (2) minimum, maximum and step distances in metres, (3) number of electrical sections in the path and for each section the relative permittivity, the conductivity in siemens/m and, for all but the last section, the end point for each section in metres from the origin, (4) the frequency loop parameters minimum frequency, maximum frequency and frequency step all in KHz and (5) the input file name for the terrain profile data (see above).

Output from W7D is written both to the screen and to a file specified by the user (or the default, TERRAIN.LIS) and an example of the first page of a multi-page output is given in Appendix IV. The terrain being modelled in this case is sinusoidal with a peak-to-peak amplitude of 10 metres, and a horizontal period of 2 km. The frequency is 10 MHz and the distance step size is 100 metres. The output columns from left to right are distance X metres along the path from the Tx position, vertical height Z metres with respect to the Tx height (the coordinate system is cartesian with its origin at the Tx), conductivity and dielectric constant at each step of the path, the magnitude and argument of the complex attenuation function F (ref 5), its magnitude in dB, and a transmission loss also in dB. The user should be aware that in this implementation of WAGNER, the computed transmission loss is 6 dB less than basic transmission loss as defined by CCIR(ref 9).

HELP files are available to assist users of W7D and associated programs, which also include WAGNER$GEN, which generates a DCL procedure file to run W7D, and WAGNER7D, a very convenient menu-based utility to run W7D interactively or in batch mode.

3.6 WAGSLAB

Hill (ref 6) has developed an enhanced version of WAGNER which is able to deal with a dielectric slab overlying irregular and inhomogeneous terrain for a vertically polarized radio transmission. With this code it becomes possible to model snow cover, urban buildings or forest vegetation.

We have used the program to estimate the effect on basic transmission loss of forest vegetation growing on an otherwise smooth spherical Earth and figure 4 shows loss along the propagation path for forests of different density at a frequency of 8 MHz.

The output of WAGSLAB is presented in ref 6 and takes a similar form to that of W7D (see Appendix IV). We note that as for W7D, the definition adopted for basic transmission loss is not that of CCIR. Furthermore, there is an added column of results giving electric field strength for a transmitter power which differs from that assumed for CCIR ground wave loss curves (ref 4), so that direct comparisons should be made with care. Our present version of WAGSLAB is also susceptible to instability when run on a VAX system since, unlike W7D, it has not been converted to double precision.

3.7 GWLSF

GWLSF is a program for performing least squares fits of a smooth spherical homogeneous Earth ground wave model to measurements of basic transmission loss, with conductivity and relative permittivity as free, adjustable parameters. It has been adapted from the program GWAVE of

Forbes (ref 8) and makes use of the residue series code of Berry and Chrisman (ref 17). In its present form it suffers from convergence difficulties for path lengths less than about 10 km and also calculates a loss which, in common with WAGNER, is 6 dB smaller than the CCIR definition. It has the advantage of generally executing more quickly than GRWAVE$FIT for paths in excess of 10 km. It has been used extensively in HFRD, and in particular for the results which appeared in ref 1. However for least squares fit applications we now prefer GRWAVE$FIT because of its direct compliance with CCIR conventions and its accommodation of path lengths less than 10 km.

3.8 SKINDEPTH

The program SKINDEPTH draws a graph of HF skin depth as a function of soil conductivity for a range of radio frequencies and a given permittivity. The program prompts the user for a value of relative permittivity and a range of values of frequency. The output is an A4 portrait format plot of skin depth, calculated according to the expression given by Hagn (ref 18, and also ref 2). The soil is assumed to be homogeneous.

Figure 5 shows an example of output from SKINDEPTH for a relative permittivity of 10 and for frequencies from 5 to 45 MHz at intervals of 5 MHz.

A HELP file is available for SKINDEPTH.

3.9 SKINMAP

The program SKINMAP draws a contour map of ground wave skin depth in metres at a specified radio frequency in conductivity-permittivity space. The output is an A4 portrait format plot of the skin depth contour map. The plot can be queued to the HP plotter if desired. Skin depth is computed according to the expression given by Hagn (ref 18 and also ref 2) for homogeneous soil.

Figure 6 shows an example of output from SKINMAP for a frequency of 5 MHz.

A HELP file is available for users of SKINMAP.

4 CONCLUSION

We have summarily described the more useful programs available on the HFRD computing system for ground wave propagation analysis applications. Greater detail may be obtained from the authors if desired. HELP files exist for most of this software to assist users.

5 ACKNOWLEDGEMENTS

The software described in this Memorandum has been acquired or developed over an extended period of time with the assistance of many individuals. For offering help and advice we particularly thank G Bass, D Bennet, R Bevensee, A Forbes, G Haack, M Golley, H Green, D Hill, J Milsom, A Smith and A Zollo.

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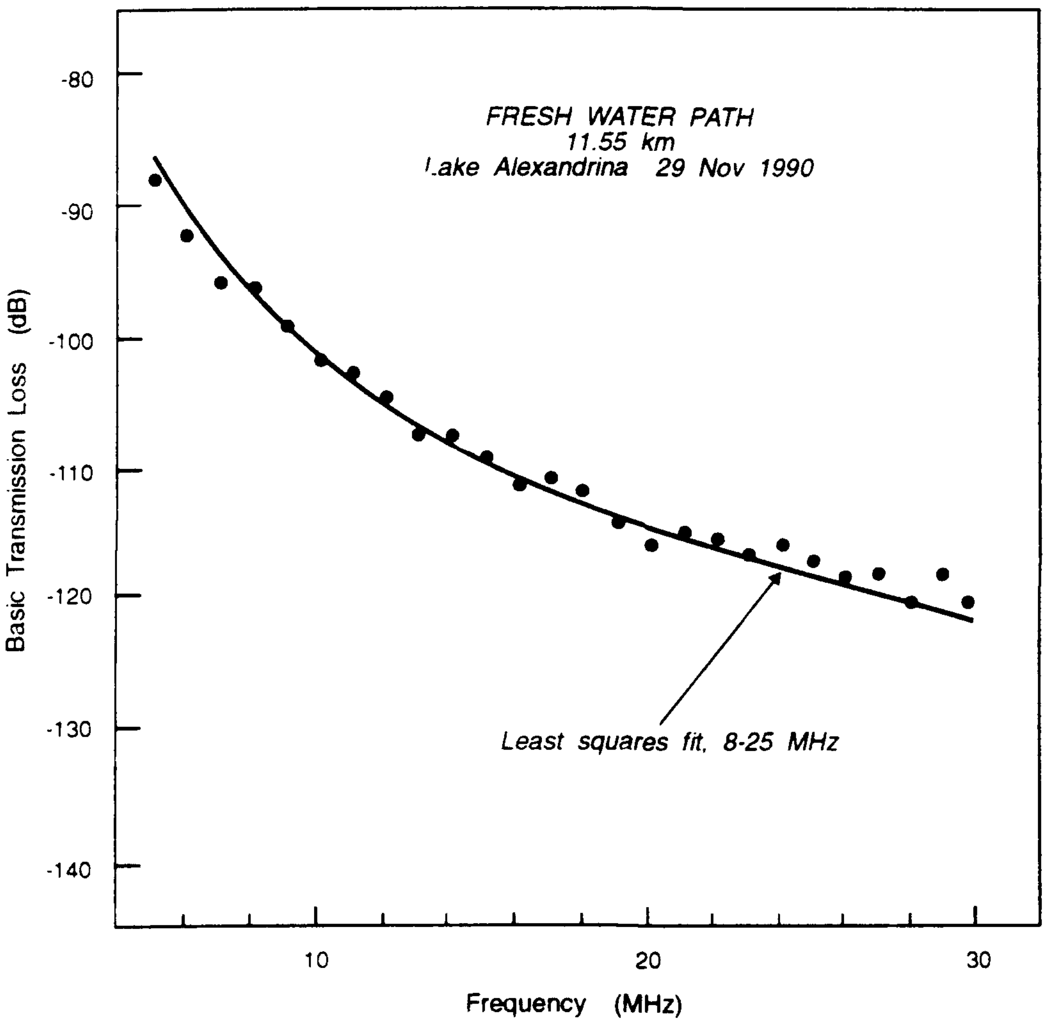

Figure 1. Graph drawn from the GRWAVE$FIT tabular output of Appendix III showing experimental loss data and best fit solution

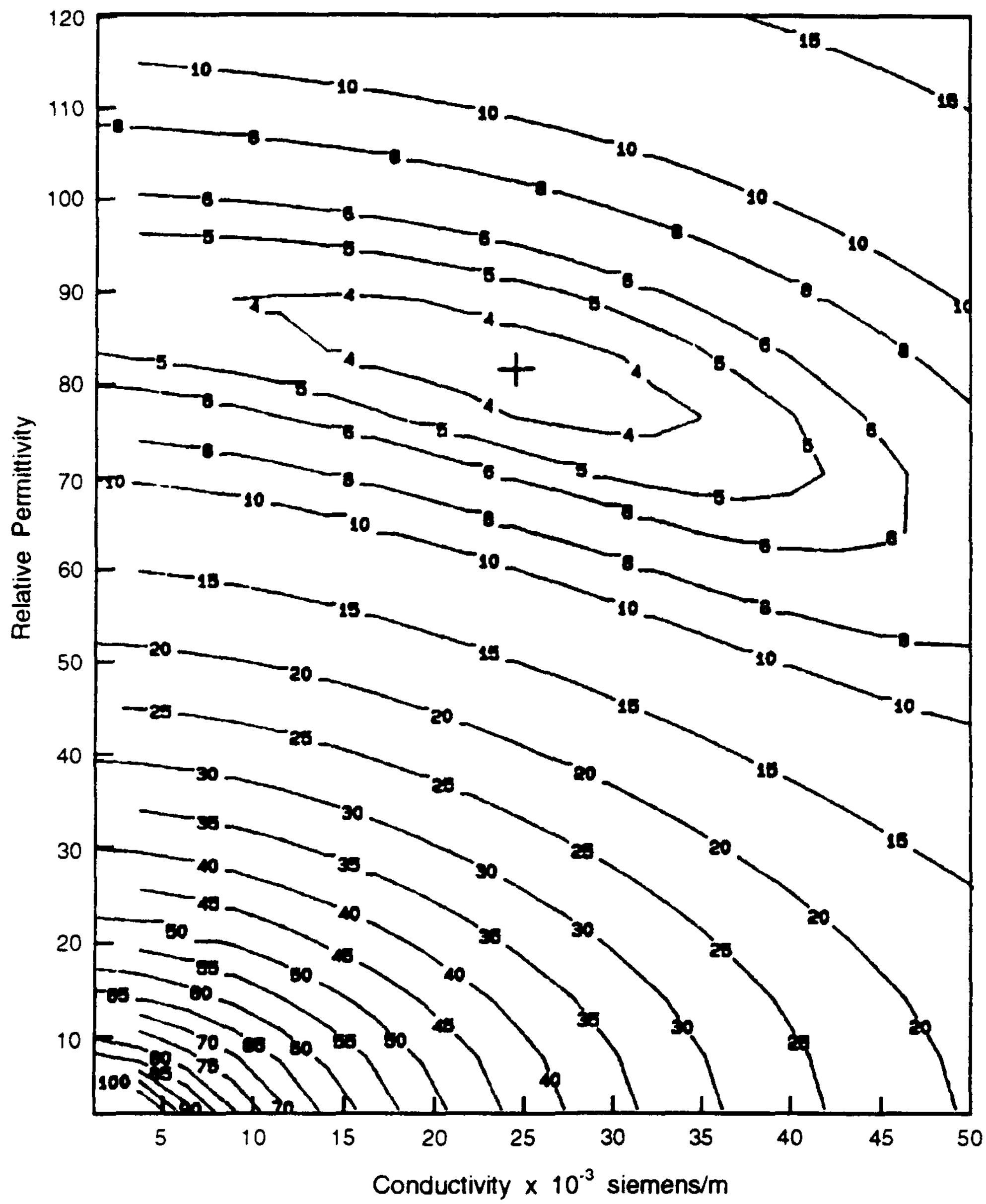

Figure 2. SPACE$PLOT output showing contours of the root mean square sum of residuals in parameter space for GRWAVE and the measurements of Figure 1.
The cross marks the least squares solution

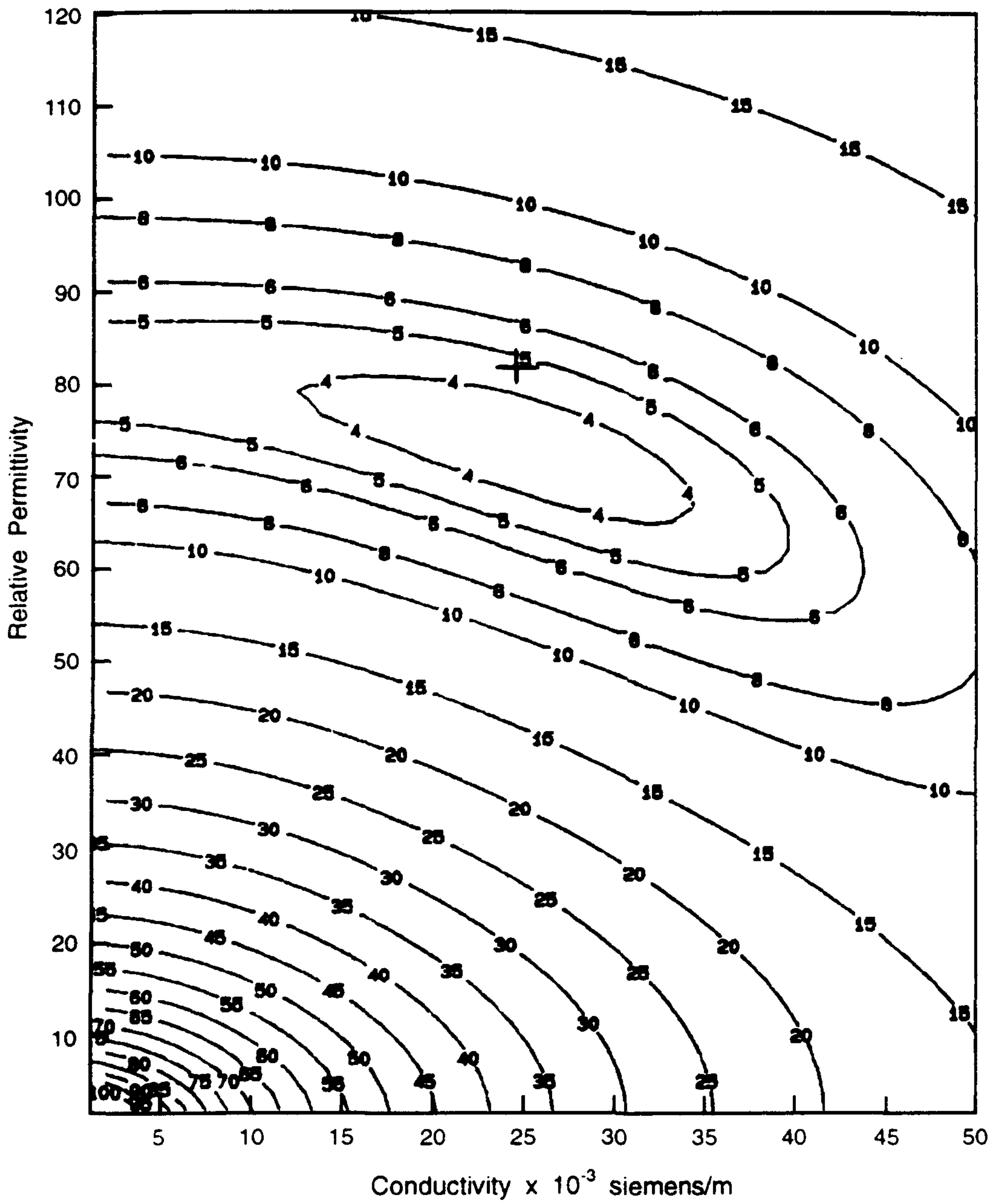

Figure 3. SPACE$PLOT output as for Figure 2
using EMPIRICAL to calculate ground wave loss residual contours.

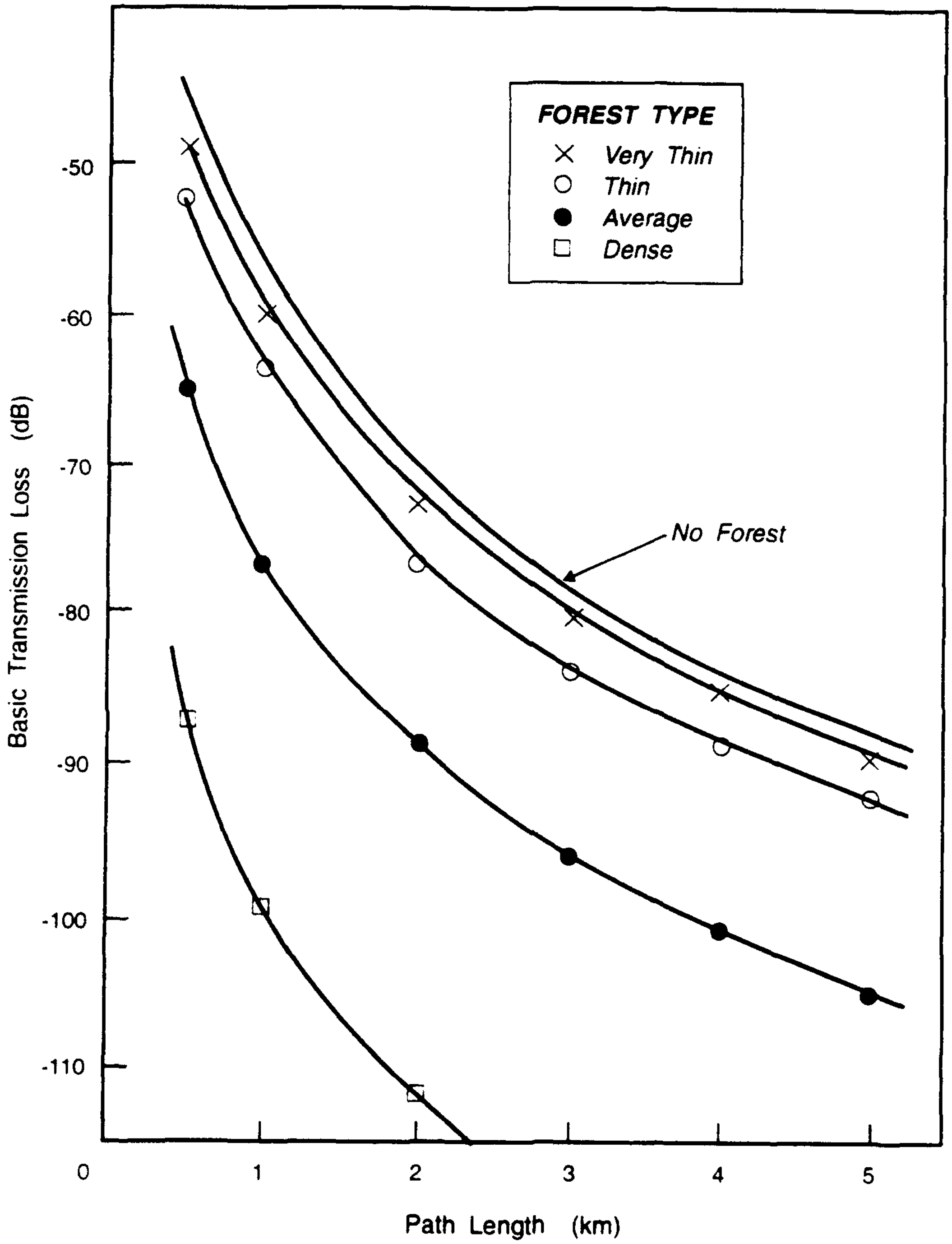

Figure 4. Graph drawn from WAGSLAB tabular output showing Loss versus Path Length for Forest Vegetation of differing density at 8MHz.

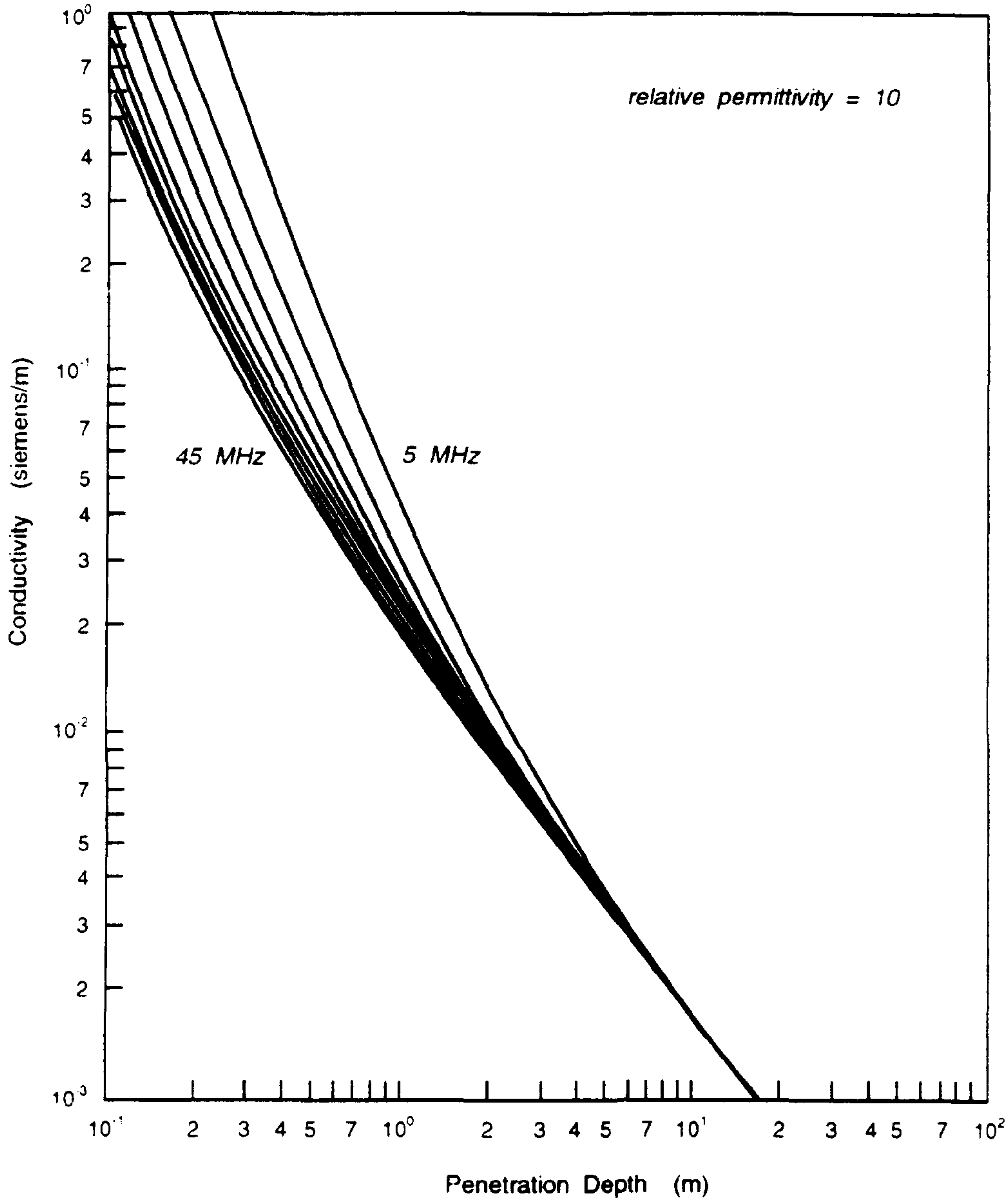

Figure 5. SKINDEPTH output as a function of soil conductivity for a relative permittivity of 10 and frequencies from 5 to 45 MHz at 5 MHz intervals.

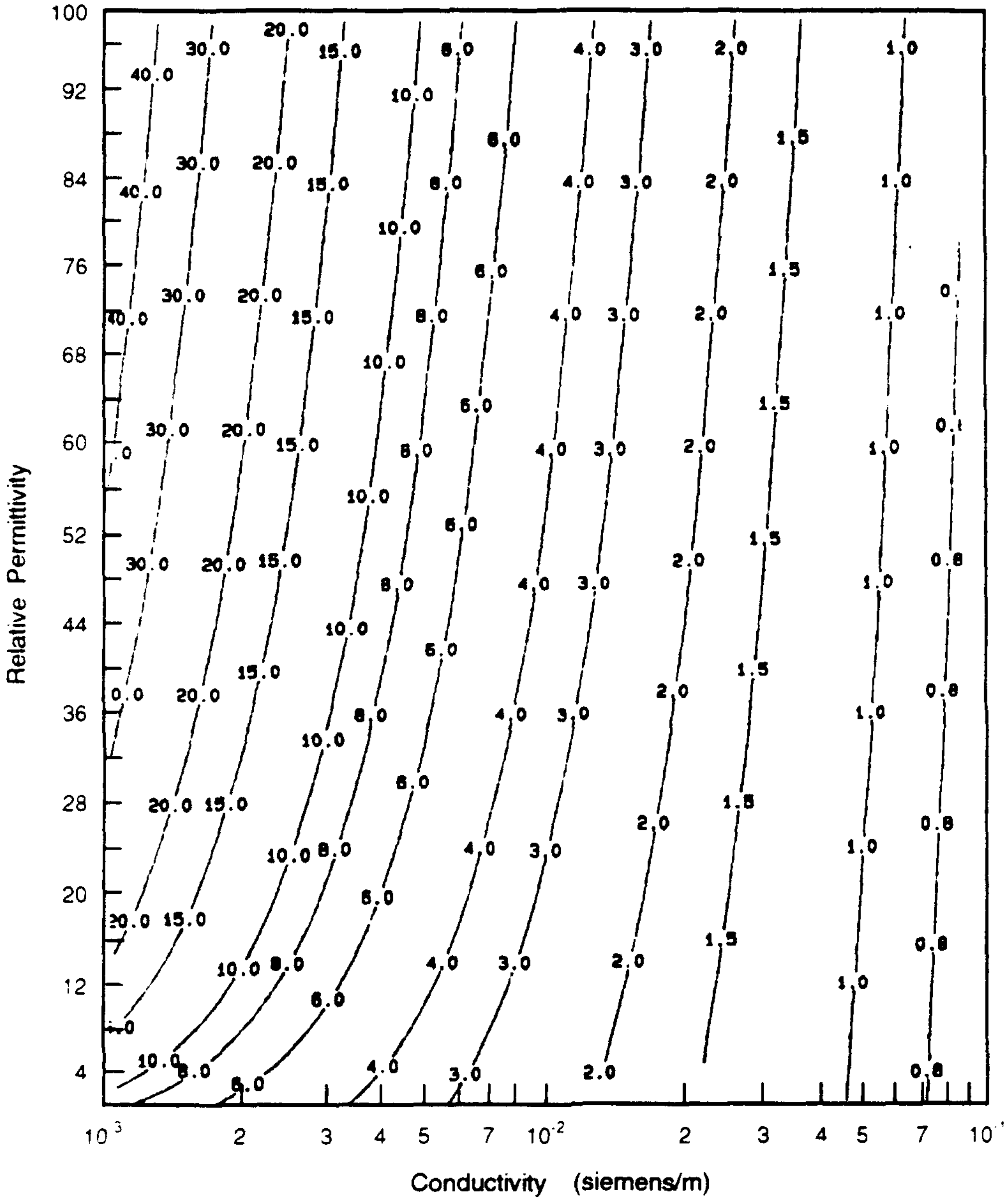

Figure 6. Output of SKINMAP showing skin depth at 5 MHz as a function of conductivity and relative permittivity.

APPENDIX I HELP file for the Program GRWAVE

GRWAVE

Subroutine GRWAVE implements a formula for Ground_wave field strength calculation. The routine resides in a file called GRWAVE_REL_2.FOR with the other (lower level) routines required to perform the calculations.

Format:

```
CALL grwave ( idebug,          ! debug flag
&             ig,              ! near/far calculation flag
&             ipolrn,          ! polarisation flag
&             loglin,          ! log or linear distance step
&             freq,            ! frequency in MHz
&             epslon,          ! relative permittivity
&             sigma,           ! conductivity in Siemens per metre
&             dmin,            ! distance (minimum) km
&             dstep,           ! distance (step) in km
&             dmax,            ! distance (maximum) in km
&             jr,              ! number of Rx heights
&             jt,              ! number of Tx heights
&             jht,             ! mode for processing Rx and Tx heights
&             hrr,             ! vector of Rx heights in metres
&             htt,             ! vector of Tx heights in metres
&             ans,             ! surface refractivity in n-units
&             hscale)          ! height scale in km for exponential
                               ! refractivity variation
```

idebug
controls the amount of debug output given.

idebug	= 0 for silent operation
	= 1 for principal input quantities and results
	= 2 for some intermediate quantities
	= 3 for comprehensive output for diagnostic purposes

ig	= -1 for far field calculations,
ig	= 1 for near field calculations or
	= 0 for both calculations.

ipolrn	= 1 for vertical polarisation or
ipolrn	= 2 for horizontal polarisation.

loglin	Log or linear distance step, refer to dstep for details.
freq	Frequency in MHz.
epslon	The relative permittivity of the earth.
sigma	The conductivity of the earth in siemens/metre.
dmin	The minimum range in km.
dstep	The range step in km, added (loglin=0) or multiplied (loglin=1) to the range at each step in FLATX3 and GEOMOP; and subtracted from (loglin=0) or divided (loglin=1) into the range at each step in RESIDH.
dmax	The maximum range in km.
jr	The number of Rx heights in hrr.
jt	The number of Tx heights in htt.
jht	The mode for processing the Rx and Tx heights. The field is computed for the following combinations of heights hrr (lr) and htt (lt). For jht=1 ((lt=1,jt),lr=1,jr). For jht=2 must have jr=jt and ((lt=lr,lr),lr=1,jr). For jht=3 must have jr=jt and ((lt=lr,jr),lr=1,jr).
hrr	The vector of Rx heights in metres.
htt	The vector of Tx heights in metres.
ans	The surface refractivity in n-units.
hscale	The height scale in km for exponential refractivity variation.

The method of calculating groundwave pathloss is described in the following references.

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APPENDIX II Sample Output from GRWAVE

```
          SELECTED VALUES FOR PROGRAM RUN ARE
IDEBUG =   1               IPOLRN =  1      (1 VERT 2 HORZ)
FREQ   =  10.000 MHZ       IG     =  0      (-1 FAR 1 NEAR 0 BOTH)
EPSLON =  80.000           SIGMA  =  5.000 S/M
HRR    =   0.000 M         HTT    =  0.000 M
DMIN   =   2.000 KM        DSTEP  =  2.000 KM
DMAX   =  50.000 KM        LOGLIN =  0
JHT    =   1               HSCALE =  7.350 KM
ATMOSPHERIC CONSTANTS
REFRACTIVITY              =  315.000 (N-UNITS)
SCALE HEIGHT              =    7.350 KM
GROUND CONSTANTS
RELATIVE PERMITTIVITY =    80.000 UNITS
CONDUCTIVITY              =    5.000 SIEMENS/METRE
VERTICAL POLARISATION
MODIFIED TERMINAL HEIGHTS
                  HR =    0.0000000E+00
                  HT =    0.0000000E+00
MINIMUM DISTANCE =    2.000   KILOMETRES
MAXIMUM DISTANCE =   50.000   KILOMETRES
DSTEP            =    2.000   KILOMETRES
FREQUENCY              =  10.000 MHZ
TRANSMITTER HEIGHT =    0.0    METRES
RECEIVER HEIGHT    =    0.0    METRES
DISTANCE              FIELD STRENGTH           BASIC TRANSMISSION LOSS
   KM                    DB(UV/M)                        DB
                                        (FLAT)
   2.00                   103.36                        58.63
   4.00                    97.23                        64.75
   6.00                    93.60                        68.39
   8.00                    90.99                        71.00
  10.00                    88.93                        73.05
  12.00                    87.23                        74.75
  14.00                    85.78                        76.21
  16.00                    84.50                        77.49
  18.00                    83.35                        78.63
  18.87                    82.89                        79.10
                                        (FAR)
  18.87                    82.91                        79.08
  20.00                    82.34                        79.64
  22.00                    81.40                        80.58
  24.00                    80.52                        81.47
  26.00                    79.70                        82.28
  28.00                    78.93                        83.06
  30.00                    78.20                        83.78
  32.00                    77.52                        84.47
  34.00                    76.86                        85.12
  36.00                    76.23                        85.75
  38.00                    75.63                        86.35
  40.00                    75.05                        86.93
  42.00                    74.50                        87.49
  44.00                    73.96                        88.02
  46.00                    73.44                        88.54
  48.00                    72.93                        89.05
  50.00                    72.44                        89.54
```

APPENDIX III Output from GRWAVE$FIT

```
RAW DATA FROM DATAFILE :IEGROUP:[GROUND_WAVE.GWD]90333AG8L26.gwd
SITE NAME AND COMMENT  :
Milang to Point Sturt (fresh water) Rod & Loop Averaged

SITE IDENTIFIER NUMBER IS 42
YEAR 1990   DAY 333

      FREQUENCY (KHZ)                 MEAS ATTEN (DB)
         8100                             96.4
         9100                             99.5
        10100                            101.9
        11100                            103.2
        12100                            105.1
        13100                            108.1
        14100                            107.9
        15100                            109.6
        16100                            111.8
        17100                            111.3
        18100                            112.5
        19100                            114.7
        20100                            116.4
        21100                            115.6
        22100                            115.9
        23100                            117.2
        24100                            116.5
        25100                            117.7

DNONLIN RESULTS:

NON-LINEAR ESTIMATION, PROBLEM NUMBER 1

  18 OBSERVATIONS,  2 PARAMETERS  86 SCRATCH REQUIRED

INITIAL PARAMETER VALUES

       1            2
  0.3500E-01  0.8000E+02

PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS

       1            2
  0.1000E-01  0.1000E-01

INITIAL SUM OF SQUARES = 0.1971E+02

                                   ITERATION NO.  1
DETERMINANT = 0.4036E+00   ANGLE IN SCALED COORD = 45.28 DEGREES
TEST POINT PARAMETER VALUES
  0.2450E-01  0.8184E+02
TEST POINT SUM OF SQUARES = 0.1175E+02
```

```
PARAMETER VALUES VIA REGRESSION

      1            2
  0.2450E-01   0.8184E+02

LAMBDA = 0.100E-02                SUM OF SQUARES AFTER
REGRESSION = 0.1174894E+02


                                      INTEGRATION NO. 2
DETERMINANT = 0.3886E+00   ANGLE IN SCALED COORD = 35.38 DEGREES
TEST POINT PARAMETER VALUES
  0.2444E-01   0.8114E+02
TEST POINT SUM OF SQUARES = 0.1167E+02

PARAMETER VALUES VIA REGRESSION

      1            2
  0.2444E-01   0.8114E+02

LAMBDA = 0.100E-03                           SUM OF SQUARES AFTER
REGRESSION = 0.1166753E+02


                                       INTEGRATION NO. 3
DETERMINANT = 0.3879E+00   ANGLE IN SCALED COORD = 18.12 DEGREES
TEST POINT PARAMETER VALUES
  0.2442E-01   0.8115E+02
TEST POINT SUM OF SQUARES = 0.1167E+02

PARAMETER VALUES VIA REGRESSION

      1            2
  0.2442E-01   0.8115E+02

LAMBDA = 0.100E-04                            SUM OF SQUARES AFTER
REGRESSION = 0.1166752E+02

ITERATION STOPS-RELATIVE CHANGE IN EACH PARAMETER LESS THAN
0.1000E-04
```

```
FINAL FUNCTION VALUES
 0.9709E+02  0.9952E+02  0.1016E+03  0.1035E+03  0.1052E+03
 0.1067E+03  0.1081E+03  0.1094E+03  0.1106E+03  0.1118E+03
 0.1128E+03  0.1138E+03  0.1147E+03  0.1156E+03  0.1165E+03
 0.1173E+03  0.1180E+03  0.1188E+03

RESIDUALS
-0.6910E+00  -0.2059E-01   0.2584E+00  -0.3225E+00  -0.1111E+00
 0.1356E+01  -0.2472E+00   0.1578E+00   0.1156E+01  -0.4656E+00
-0.3173E+00   0.8925E+00   0.1657E+01  -0.3013E-01  -0.5733E+00
-0.7684E-01  -0.1544E+01  -0.1079E+01

CORRELATION MATRIX

        1           2
 1   1.0000
 2  -0.7824      1.0000

NORMALISING ELEMENTS

      1           2
  0.5906E-02  0.4126E+01

VARIANCE OF RESIDUALS = 0.7292E+00, 16 DEGREES OF FREEDOM

INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER  (ON LINEAR
HYPOTHESIS)

      1           2
  0.3451E-01  0.8820E+02
  0.1433E-01  0.7411E+02

APPROXIMATE CONFIDENCE LIMITS FOR EACH FUNCTION VALUE
 0.9817E+02  0.1004E+03  0.1023E+03  0.1041E+03  0.1057E+03
 0.1072E+03  0.1086E+03  0.1098E+03  0.1111E+03  0.1122E+03
 0.9601E+02  0.9869E+02  0.1010E+03  0.1030E+03  0.1048E+03
 0.1063E+03  0.1077E+03  0.1090E+03  0.1102E+03  0.1113E+03
 0.1133E+03  0.1143E+03  0.1152E+03  0.1161E+03  0.1170E+03
 0.1178E+03  0.1186E+03  0.1194E+03
 0.1124E+03  0.1133E+03  0.1142E+03  0.1151E+03  0.1159E+03
 0.1167E+03  0.1175E+03  0.1182E+03

END OF PROBLEM NO. 1

     GROUND CONSTANTS:
     RELATIVE PERMITTIVITY = 81.15361 UNITS
     CONDUCTIVITY          =  0.02442 SIEMENS/METRE
```

APPENDIX IV Output from WAGNER version W7D

Sinusoidal terrain, Amp. (pk-pk)=10m, period=2.00 km, offset=0.00 km
buffer

DISTANCES FROM 100 TO 10000 IN 100 M STEPS

SMOOTH SPHERE RADIUS 0.850E+07 METRES ON PLATEAU OF 0 METRES ALTITUDE

FREQ = 10.00 MHZ VERT POLARISATION ANTENNA HEIGHT = 0.00 METRES

X (M)	Z (M)	COND (MHO/M)	DIEL CONST	F(X) MAG	F(X) ARG	F DB	ATT DB
0.00	0.000	0.05	10.0	0.100E+01	0.000E+00	0.0	0.0
200.00	-0.002	0.05	10.0	0.862E+00	-0.829E+00	-1.2	-33.7
400.00	-0.009	0.05	10.0	0.767E+00	-0.115E+01	-2.3	-40.7
600.00	-0.021	0.05	10.0	0.688E+00	-0.139E+01	-3.4	-45.2
800.00	2.962	0.05	10.0	0.595E+00	-0.159E+01	-4.5	-48.9
1000.00	4.941	0.05	10.0	0.570E+00	-0.171E+01	-4.8	-51.3
1200.00	4.915	0.05	10.0	0.510E+00	-0.187E+01	-5.8	-53.8
1400.00	2.884	0.05	10.0	0.442E+00	-0.204E+01	-7.0	-56.4
1600.00	-0.150	0.05	10.0	0.382E+00	-0.220E+01	-8.3	-58.8
1800.00	-0.190	0.05	10.0	0.395E+00	-0.224E+01	-8.0	-59.5
2000.00	-0.235	0.05	10.0	0.351E+00	-0.233E+01	-9.0	-61.5
2200.00	-0.284	0.05	10.0	0.320E+00	-0.240E+01	-9.8	-63.1
2400.00	-0.338	0.05	10.0	0.293E+00	-0.247E+01	-10.6	-64.6
2600.00	-0.397	0.05	10.0	0.270E+00	-0.253E+01	-11.3	-66.0
2800.00	2.539	0.05	10.0	0.240E+00	-0.257E+01	-12.3	-67.7
3000.00	4.470	0.05	10.0	0.236E+00	-0.256E+01	-12.5	-68.4
3200.00	4.397	0.05	10.0	0.217E+00	-0.262E+01	-13.2	-69.7
3400.00	2.320	0.05	10.0	0.192E+00	-0.271E+01	-14.2	-71.3
3600.00	-0.761	0.05	10.0	0.170E+00	-0.280E+01	-15.3	-72.9
3800.00	-0.849	0.05	10.0	0.180E+00	-0.279E+01	-14.8	-72.8
4000.00	-0.940	0.05	10.0	0.163E+00	-0.283E+01	-15.7	-74.1
4200.00	-1.037	0.05	10.0	0.152E+00	-0.285E+01	-16.3	-75.2
4400.00	-1.138	0.05	10.0	0.143E+00	-0.287E+01	-16.8	-76.1
4600.00	-1.244	0.05	10.0	0.134E+00	-0.289E+01	-17.4	-77.0
4800.00	1.645	0.05	10.0	0.122E+00	-0.289E+01	-18.2	-78.2

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17 SUMMARY OR ABSTRACT
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This document describes a variety of in-house and externally written software which has been used in High Frequency Radar Division for the prediction and analysis of ground wave propagation losses. Applications of the software have included the determination of sizes of HF array buffer zones and intersite separations between transmitter and receiver for Over-The-Horizon Radars of the Jindalee Operational Radar Network. The same software may also be useful for communications and broadcasting applications, and can be made available upon consultation with the authors.

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